Development of Computer Aided Process Planning System for Plate Bending by Line-Heating (Report II)†

—Practice for Plate Bending in Shipyard Viewed from Aspect of Inherent Strain—

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Abstract

In the plate bending process by line-heating, the decisions on which part of the plate should be heated and in which direction are usually made by skillful workers. However, the number of skilled worker is reducing rapidly and this becomes a serious problem in shipyard today. To solve this, the authors proposed a method to make these decision based on theoretical analyses focussed on inherent strain in the previous report. The potential usefulness of the method were demonstrated through example problems dealing with mathematical ideal geometry. In this report, comparison between the theoretical prediction and the real practice in the shipyard to form curved members of ship hull are made and it is attempted to visualize the knowledge of skilled workers, which was unvisible, using computer graphic images showing inherent strain. Further, it is demonstrated that the same idea can be applied not only to make decisions on line-heating process but also to design the total plate bending process including those using the bending roller and the press machine.

KEY WORDS: (Line Heating) (Inherent Strain) (Forming Procedure) (Plate Forming System) (Real Models) (Finite Element Method) (Computer Aided System)

1. Introduction

The line heating method has been widely used to form curved plates of ship's hull in shipyards. The most significant feature of this method is its potential to form complex shape which is commonly found in manufacturing shell plating of ship structures. Forming a flat plate to fit such surface is a kind of creating a 3-dimensional complex curved surface. The experience and skill of workers are considered to be the most important factors in the forming process by manual line heating. As a matter of fact, this kind of workers is disappearing day by day and it is causing a serious problem for the shipbuilding industry. Automation of plate forming using the line heating method nowadays has been an essential objective for many shipyards. Recently, new theoretical attempts have been made to realize the automation of plate forming using the line heating and other methods[1)–6)].

The authors investigated in the first report the relation between the final form of the plate and the inherent strain to be given for plate bending using the Finite Element Method. The characteristics of the inherent strain for forming curved shapes were clarified[6)]. Also, a method for predicting the direction and the position of heating lines was proposed. The validity of the proposed method was examined with mathematical ideal curved surfaces. This report is devoted to present the correlation between the inherent strain of the typical curved surfaces of actual shell plating and the real plate forming practice. Also, an experiment was carried out to form simple twisted shape and the result is compared with the theoretical prediction. Although, attention is paid to the inherent strain and its components in the proposed method of plate forming, a total system to design the process of plate forming in which a roll bending and/or press bending, etc. as well as the line heating are employed has been also proposed.

2. Forming Simple Twisted Shape

2.1 Model of analysis

In the previous report, the geometries of the pillow and the saddle shapes were represented mathematically by

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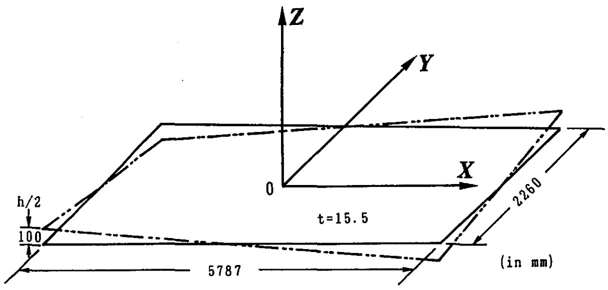
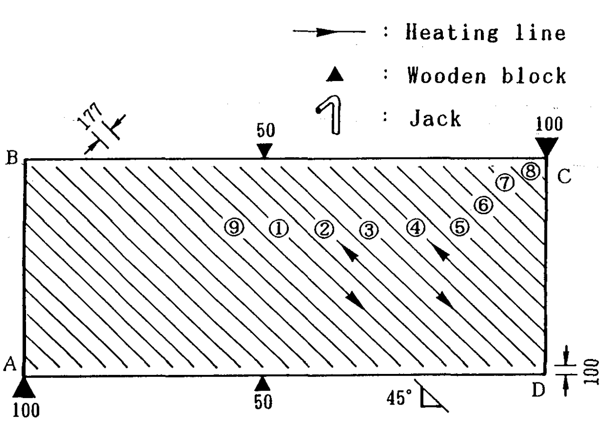
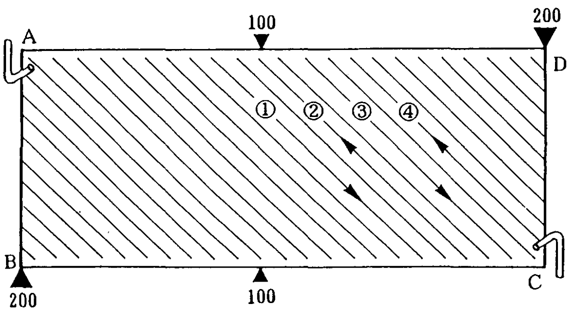


Fig. 1 Model for experiment (twisted shape).



(a) face side



(b) back side

Fig. 2 Actual plate forming procedure.

Table 1 Condition of line heating.

heating burner	L-200S (Koike Sanso)
gas pressure LPG	0.5 atm*
gas pressure oxygen	5.0 atm*
traveling speed of burner	face: 1.6 m/min back: 2.1 m/min

(*) gas pressure at the connecter of piping system in the work. valve for LPG is kept full open and that for oxygen is adjusted so that the ratio between their volumes becomes 1:4.

second order functions of the coordinates x and y such that,

$$\text{pillow shape}: w_0(x,y) = ax^2 + by^2 + c \tag{1}$$

$$\text{saddle shape}: w_0(x,y) = ax^2 - by^2 + c \tag{2}$$

Similarly, the simple twisted shape can be given as follows,

$$\text{twisted shape}: w_0(x,y) = axy \tag{3}$$

where a, b and c are constants.

The dimensions of the model used in the experiment as well as the theoretical analysis are shown in **Fig. 1**. The height, $h/2$, at the corners of the plate is 100 mm. The difference in heights between any two successive corners, h, represents the magnitude of twisting. The same magnitude of twisting is attempted to be achieved in the experiment.

2.2 Experimental procedure

The line heating method was used in the experiment. The forming procedures were carried out as follows:

1) The position and direction of heating lines were marked on the plate. Each heating line is inclined by an angle 45° relative to the long edges as shown in **Fig. 2-a**. The interval between any two heating lines is equal to 177 mm. Each heating line is ended at 100 mm away from the long edges.
2) The first heating line started nearly from the middle of the plate, i.e., the line number 1. The sequence and direction of heating lines are shown in the figure. The heating conditions are given in **Table 1**.
3) To distinguish the face and back sides on the drawing, the corners of the plate are denoted by A, B, C and D.
4) During the heating process on the face side, the corners A and C were raised gradually till their heights became 100 mm at the end of the heating process. In addition, the middle of the long edges were raised till their heights reached 50 mm.
5) After finishing the heating process for the face side, the back side was prepared in the same procedures given in steps (1) and (2). The relative position of the plate corners with respect to the back side are shown in Fig. 2-b. It is obvious that the heating lines on this side are perpendicular to that on the face side.
6) For this side, the corners B and D were raised up to 200 mm, while the middle of the long edges were raised by 100 mm. On the contrary, the corners A and C were prevented from deflection using jacks as shown in the figure.
7) During the heating process on both sides, water was used for cooling on the heated surface.

2.3 Inherent strain distribution

Applying the same procedure given in the first report[6], the plate is forced to deform to the final shape to be formed and the bending and the inplane inherent strains are computed using the Finit Element Method. Based on the strain distributions and the predominant component, decisions on rolling process as well as the position and the direction of heating lines can be given. However, in this analysis the exact spacing of heating lines will not be estimated since the relation between the heating condition and the inherent strain is not known at the present stage of research. The aim of this report is to show the correlation between the inherent strain and the forming process as stated previously. The distributions of the principal bending and inplane inherent strains, ε^b and ε^m, for the simple twisted shape are shown in Figs. 3 and 4, respectively.

The magnitudes of the two bending inherent strain components shown by the length of the arrows are equal to each other. In addition, one component is inclined by an angle 45° relative to the plate. As it can be seen from **Fig. 3**, the bending inherent strain is only developed by the shear bending strain, such that,

$$(\partial^2 w_0/\partial x^2) = (\partial^2 w_0/\partial y^2) = 0.0 \quad (4)$$

$$(\partial^2 w_0/\partial x\ \partial y) = a \quad (5)$$

It is clear from Eq. (5) that the bending inherent strain is constant throughout the plate. The absolute value of the bending inherent strain, ε^b, is equal to 4.52×10^{-4} which is twice of the maximum absolute value of inplane inherent strain, $|\varepsilon^m{}_{max}| = 2.92\times10^{-4}$. Therefore, the bending component is the predominant one in this example. Bending of the plate can be done by rolling machine in one direction and by line heating in the other direction or using line heating for both directions as it was done in the experiment. The position and direction of heating line is decided according to the strain distribution given in Fig. 3. The heating lines will be distributed throughout the plate with equal distance from each other owing to the uniform

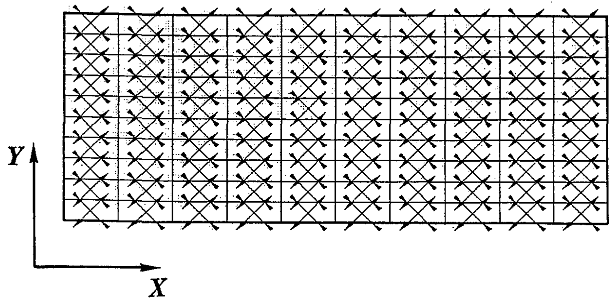


Fig. 3 Distribution of bending inherent strain for twisted shape.

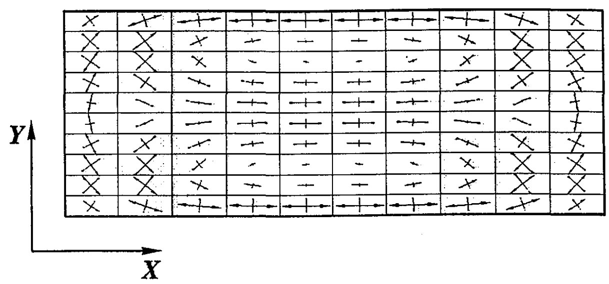


Fig. 4 Distribution of inplane inherent strain for twisted shape.

distribution of the bending inherent strain. The direction of heating lines on the face and the back sides must be perpendicular to each other and they are inclined by angle 45° relative to the longitudinal edge. This theoretical prediction for the distribution of heating lines is in correspondence with the real practice of the experiment.

As for the inplane inherent strain, shown in **Fig. 4**, the maximum value of tensile inherent strain appears at middle of the long edges. On the other hand, the maximum compressive strains are observed in middle portion of the plate. To account for the tensile inplane inherent strain at the long edges, the heating lines should not be extended to these edges. Also, this conclusion is in agreement with the real practice.

2.4 Magnitude of twisting and bending methods

The bending deformation of plate is caused by various means. The causes of the deformation may be conveniently classified into the following:

1) elastic or natural deformation by gravitational force,
2) bending of plate due to bending inherent strain which is created by rolling machine.
3) bending of plate due to bending inherent strain which is created by line heating method.
4) bending of plate due to inplane inherent strain which is created by line heating method.

To clarify the contributions of these, different analyses were made for the simple twisted shape shown in Fig. 1. At first, the flat plate, for which the magnitude of twisting h to be achieved is equal 100 mm, is deformed under its own weight. The distribution of error in geometry due to this process is shown in **Fig. 5**. The points shown in this figure represent the location of the supporting blocks the height of which is adjusted to the geometry to be formed. The solid circle means that the point is in contact with the block while the open circle means out of contact. The maximum error in geometry due to the gravitational force only is equal to 87 mm. If only the bending inherent strain is given to the flat plate, about 83% of the required form can be obtained and the resulting error becomes 17%.

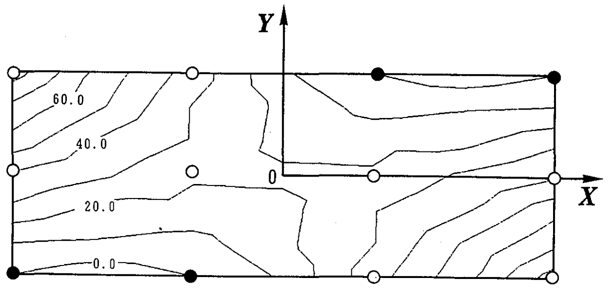


Fig. 5 Distribution of error in geometry of flat plate deformed under gravitational force (h = 100 mm).

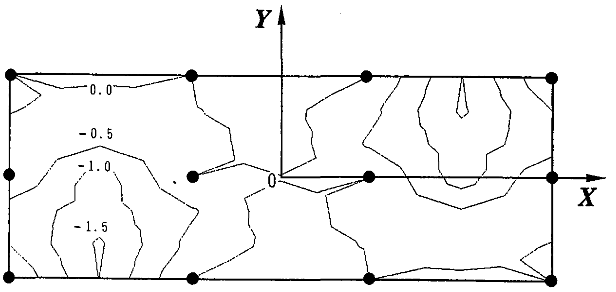


Fig. 6 Distribution of error in geometry of plate with bending inherent strain deformed under gravitational force (h = 100 mm)

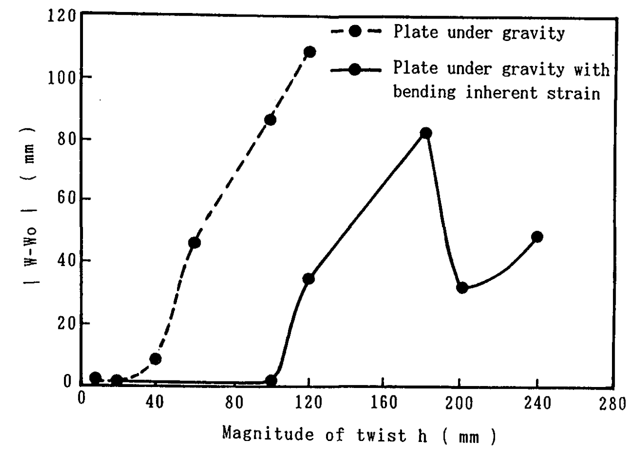


Fig. 7 Relation between the maximum error in geometry of plate and the magnitude of twisting.

Further if the effect of gravitational force is considered, the geometry of the plate which is bent by bending inherent strain becomes close to the desired form and the error is reduced to 1.5% as shown in **Fig. 6**.

To clarify the relation between the maximum error in geometry of the plate and the magnitude of twisting h, series of computations are made as shown in **Fig. 7**. It shows the maximum error in geometry of deformed flat plate, $|w\text{-}w_0|$, due to applying the gravitational force only and that due to the bending inherent strain with the gravity, for different magnitudes of twisting h. It is clear from this figure that for magnitude of twist up to 20 mm, the natural deformation by gravitational force is satisfactory. On the other hand, if the bending inherent strain is added, the magnitude of twisting h which can be achieved increases to about 100 mm. Above this value, the error in geometry increases until h reaches 180 mm. After that it decreases till h approaches 200 mm. This is due to the change in mode of deformation, and the error increases again as h increases. Such error is caused by neglecting the effect of the inplane inherent strain.

To compare the relative infulence of bending and inplane inherent strains with respect to the magnitude of twisting, the maximum absolute value of both components versus different values of h are shown in **Fig. 8**. It is obvious from this figure that the bending inherent strain has a linear relationship with the magnitude of twisting h. Contrary to that, the inplane inherent strain has a nonlinear relationship. The maximum value of the inplane strain component is negligible compared with bending strain component till the value of h reaches 100 mm. This conclusion is in agreement with the preceding one drawn from Fig. 7. The magnitude of the maximum inplane inherent strain becomes equal to that of the bending strain at h = 400 mm and becomes greater after that.

The residual stress created in the plate by giving the bending inherent strain may have an effect on the subsequent processes. The distribution of the inplane residual

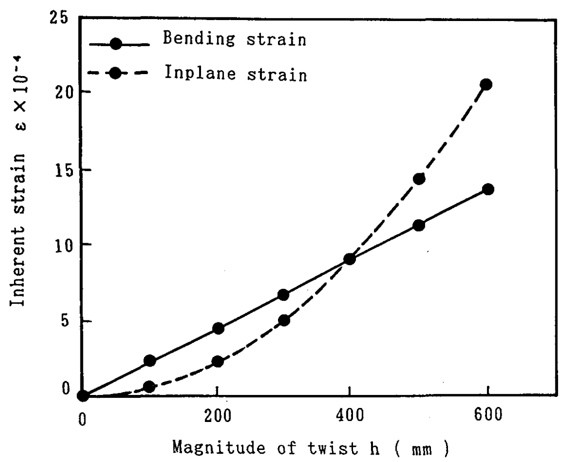


Fig. 8 Relation between the maximum inherent strains and the magnitude of twisting.

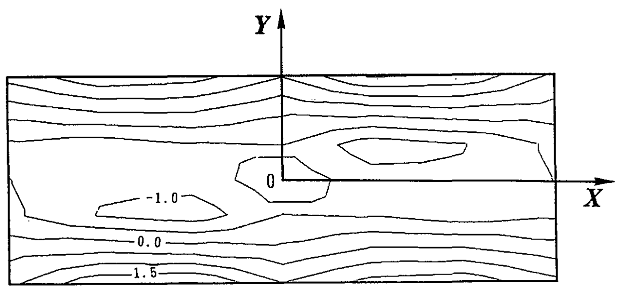


Fig. 9 Inplane stress distribution of plate with bending inherent strain in deformation under gravitational force.

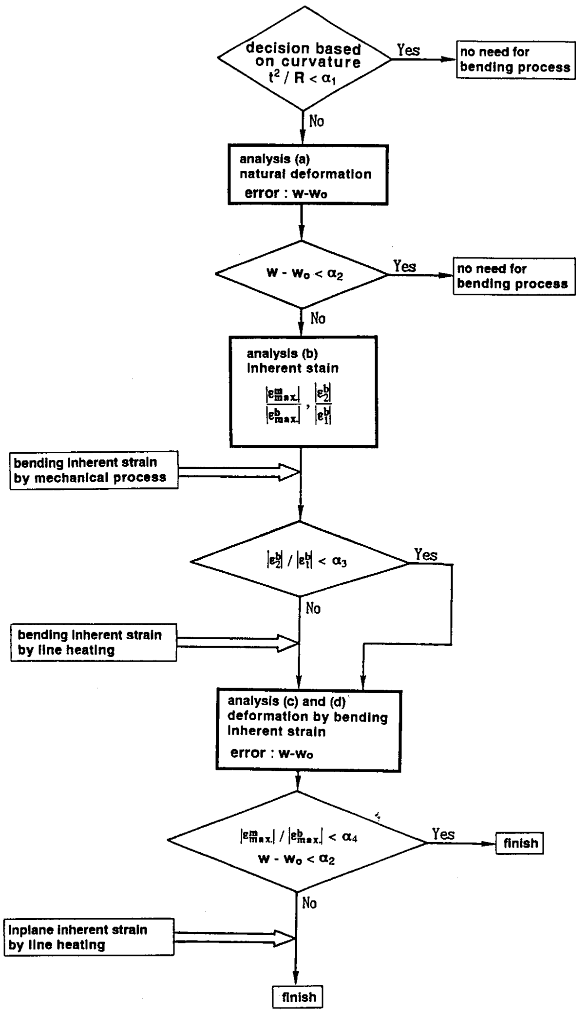


Fig. 10 Flowchart of the process design for plate bending.

stress in x direction due to applying the bending inherent strain with the gravity in the case of $h = 100$ mm is shown in **Fig. 9**. The magnitude of the inplane residual stress is small compared with the level of yield stress. The compressive stresses are concentrated in the middle portion, while the tensile stresses are observed near the long edges.

3. General Plate Forming Process

In the previous chapter, the procedure of forming simple twisted shape using rolling or press process and the line heating process was discussed. In addition, the effect of the gravity is studied. Based on this study, rough image of a general system to generate the plate forming process including rolling, press and line heating processes can be proposed. The flowchart of the plate forming process is shown in **Fig. 10**. Four different types of analyses denoted by (a), (b), (c) and (d) are considered. The behaviour of the plate is assumed to be elastic and elastic large deformation FEM code is used as a method of analysis. In these analyses, the following calculations are carried out,

a) The natural deformation of the plate under gravitational force is computed as a contact problem in which the plate is assumed to be resting on a set of supporting blocks with height adjusted to the final geometry to be achieved.
b) The distribution of the inherent strains, ε^b and ε^m, and their magnitudes are computed through the analysis of forced deformation of a flat plate to the desired final shape.
c) The deformation of the flat plate due to the bending inherent strain as well as the gravitational force is computed as a contact problem as in a).
d) The deformation of the flat plate due to bending inherent strain alone is calculated. In this case the problem should not be treated as a contact problem.

These analyses are carried out where the place shown by thick rectangular frames. In the same frames, parameters to be computed are also given. The diamond frames show decisions to be made, and α_1, α_2 and α_3 are the critical values. However, exact value of these are not known at the present stage of research. Rectangular frames in the left of the flowchart show the necessary bending process. According to Fig. 10, the total process of forming the plate can be described as follows:

1) From the required curvatures of the plate to be formed and its thickness, it is decided whether only the natural deformation is acceptable or not[7].
2) For plate in the boundary zone in the above decision, the natural deformation of the plate is analyzed and the error in the geometry $|w\text{-}w_0|$ is computed. Based on $|w\text{-}w_0|$, a need for bending process is decided.
3) The bending and inplane inherent strains distribution required to form the flat plate to the desired one are computed. The following items are calculated:
   The predominant component can be determined by the ratio between the maximum values of inplane and bending inherent strains, such as,

   $$|\varepsilon^m_{max}| / |\varepsilon^b_{max}|$$

   The degree of doubly curved nature can be represented by the ratio between the maximum values of bending inherent strains in the two principal directions, such that,

   $$|\varepsilon^b_2| / |\varepsilon^b_1|$$

4) From the ratio $|\varepsilon^b_2| / |\varepsilon^b_1|$, the direction of the predominant bending strain can be found.
5) If bending inherent strain in one direction is dominant, necessary bending inherent strain can be produced by a

mechanical process, such as rolling or press process.

6) If the two principal directions have significant bending inherent strain, a mechanical process can be applied for one direction at first. Subsequent to that, the line heating process is applied to the second direction as mentioned in the case of simple twisted shape.
7) If the bending inherent strain as well as the weight of the plate are not enough to form the plate, the compressive inplane inherent strain can be added using the line heating process.
8) From the inplane inherent strain distribution, the direction and the position of heating lines can be decided.

4. Forming of Typical Ship Hull Plates

4.1 Typical geometry of hull plates

Shell platings of ship structure for Bulk-Carrier, which has 32,000 ton deadweight, were chosen as examples. Three typical forms of curved plates, which are considered, are shown in **Figs. 11-a,b,c** with contour lines. The geometrical characteristics of these forms are categorized as pillow shape, saddle shape and twisted shape. The positions of these curved plates in the ship structure are the bow and the stern of the ship. The length, the breadth and the thickness of each plate are shown in Fig. 11.

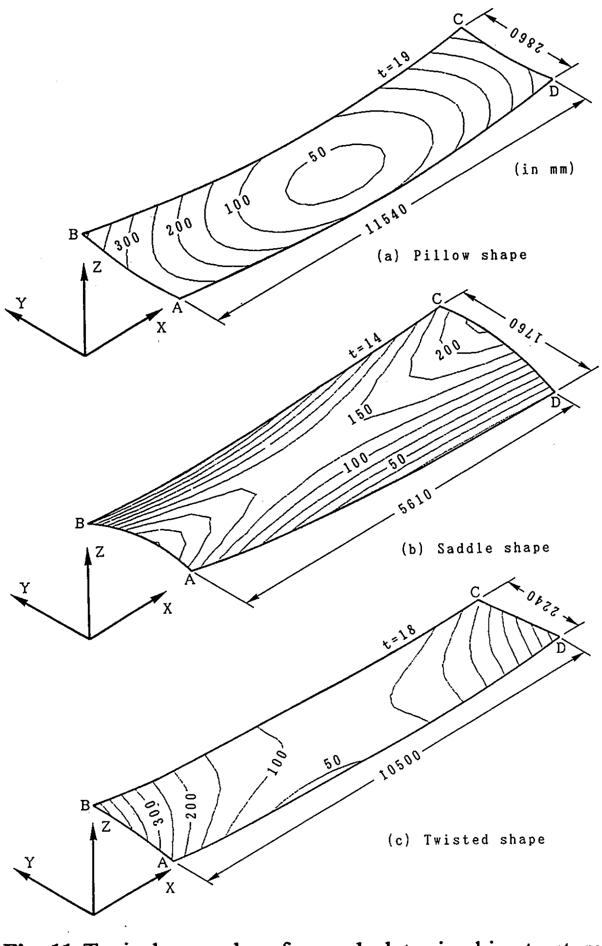


Fig. 11 Typical examples of curved plates in ship structure.

4.2 Natural forming process

It is obvious that bending of plate under its own weight is limited to cases with small curvature. The governing parameters in this process are t^2/R_1 and t^2/R_2[7]. The maximum acceptable value of this parameter for successful natural plate forming is given such that $t^2/R < 10^{-2}$. In case of the three typical models, the maximum value of this parameter is 2.4, 8.1 and 5.0 $\times$ 10^{-2} for pillow, saddle and twisted shapes, respectively. As it is expected, deformation under its own weight is not enough to achieve the desired final form.

4.3 Inherent strain distribution

The distribution of the principal bending and inplane inherent strains, given as vector components, for the three models are shown in **Fig. 12** and **13** respectively. The length of each arrow in these figures represents the scaled value of the strain in each element. The bending inherent strain distribution for each case is examined at first. In case of the pillow shape, the bending inherent strain is almost

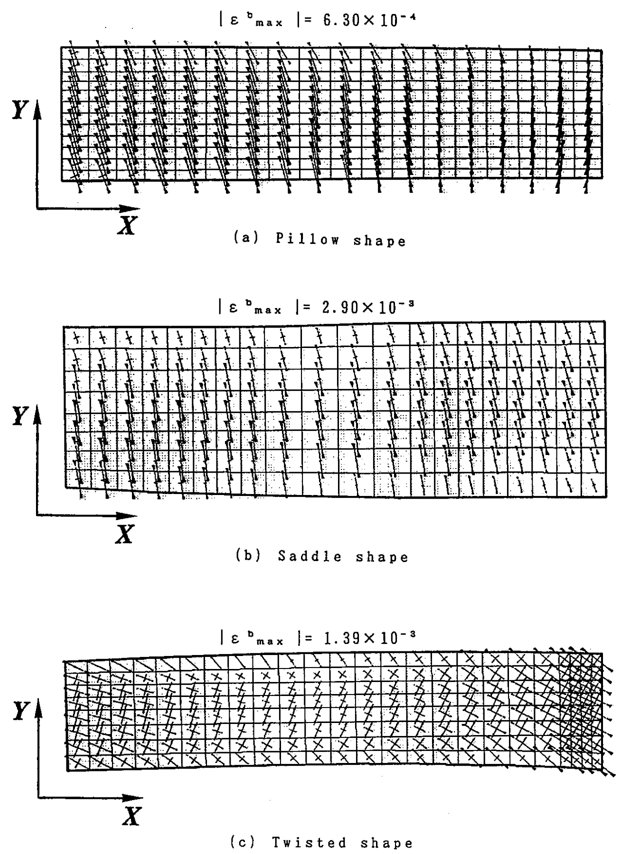


Fig. 12 Distribution of bending inherent strain.

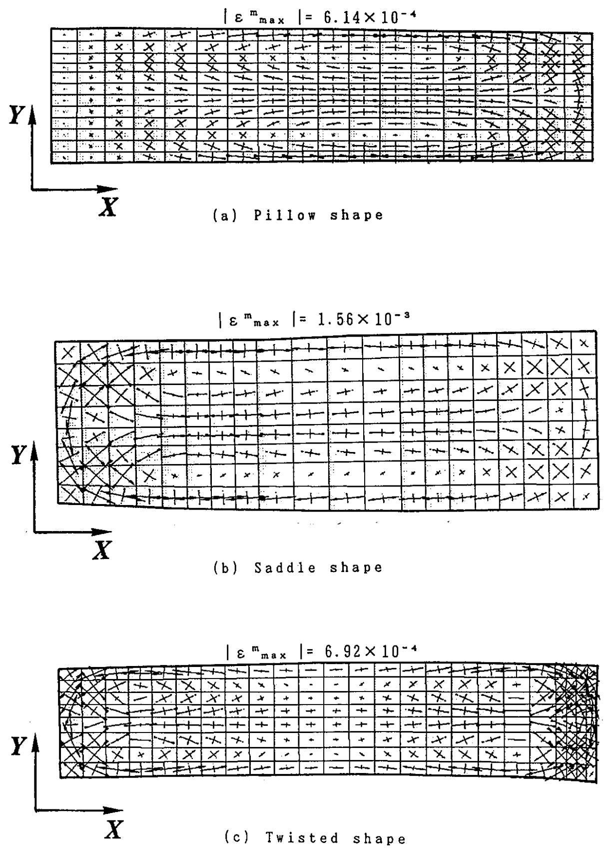


Fig. 13 Distribution of inplane inherent strain.

Table 2 Maximum bending and inplane inherent strains for the three typical curved plates.

	pillow shape	saddle shape	twisted shape
$\mid \varepsilon^b_{max} \mid$	6.3×10^{-4}	2.9×10^{-3}	1.4×10^{-3}
$\mid \varepsilon^m_{max} \mid$	6.2×10^{-4}	1.6×10^{-3}	6.9×10^{-4}
$\mid \varepsilon^m_{max} \mid / \mid \varepsilon^b_{max} \mid$	0.98	0.55	0.50
$\mid \varepsilon^b_1 \mid$	6.3×10^{-4}	2.9×10^{-3}	1.4×10^{-3}
$\mid \varepsilon^b_2 \mid$	1.3×10^{-4}	3.8×10^{-4}	8.5×10^{-4}
$\mid \varepsilon^b_2 \mid / \mid \varepsilon^b_1 \mid$	0.21	0.13	0.61

uniform throughout the plate and the bending is dominant in one direction. For the saddle shape, the same conclusion can be drawn as shown from the ratio $\varepsilon^b_2/\varepsilon^b_1$ given in **Table 2**. As for the twisted shape, the bending inherent strain in the two directions have almost the same magnitude, which is different from the other two cases. Consequently, for forming the pillow and the saddle shapes, the mechanical process can be applied effectively due to the fact that the bending strain distribution is prevailing in one direction. For the twisted shape, the rolling process may be applied for bending in one direction and the other direction can be done using the line heating.

As for the inplane inherent strain component, the relative dominance of the inplane component can determined from Table 2 in which the ratio $\varepsilon^m_{max} / \varepsilon^b_{max}$ for each case is given. It is clear that the effect of the inplane inherent strain upon the forming process of the pillow shape is of the same order compared to that of the bending inherent strain. On the other hand, for the saddle and the twisted shapes, the effect of the inplane inherent strain on the forming process is nearly the half of that of the bending inherent stain.

4.4 Mechanical forming process

The mechanical forming process can be applied effectively for the pillow and the saddle shapes as stated above. The bending strain distribution for these two cases is nearly in one direction. Although the bending inherent strains are large in the two directions, the twisted shape has a nearly uniform bending directions. Thus the bending in one direction can be achieved using the mechanical process. For the bending in the other direction, the line heating process can be applied.

4.5 Line heating process

As it is clear from the bending strain distribution shown in Fig. 12, the twisted shape cannot be achieved by the mechanical process alone which produce bending inherent strain in one direction. Therefore, after using the mechanical bending for one direction, the other direction can be bent using the line heating process. In addition, the inplane inherent strain is given using the line heating process. In the cases of pillow and saddle shapes, after the mechanical process has been completed, line heating is applied to give the inplane inherent strain.

4.6 Bending deformation

The resulting deformation after applying the bending inherent strain as well as making use of the gravitational force can be determined by the analysis (c) or (d) in the flowchart. **Figs. 14-a,b,c** show these deformations for the pillow, the saddle and the twisted shapes, respectively. It is clear from Fig. 14 that giving only bending inherent strain and taking the advantage of the gravitational force are not sufficient to get the desirable form. The deformed middle cross-section for each plate, shown in Fig. 14, are compared with the final geometry to be obtained in **Fig. 15**. These results provides information about to what extent the bending of plate in one direction is necessary, i.e., the plate should be over bent or under bent with respect to the final form. From this figure it can be concluded that an over bending is required for the pillow and the saddle shapes.

The bending and inplane residual stress distributions

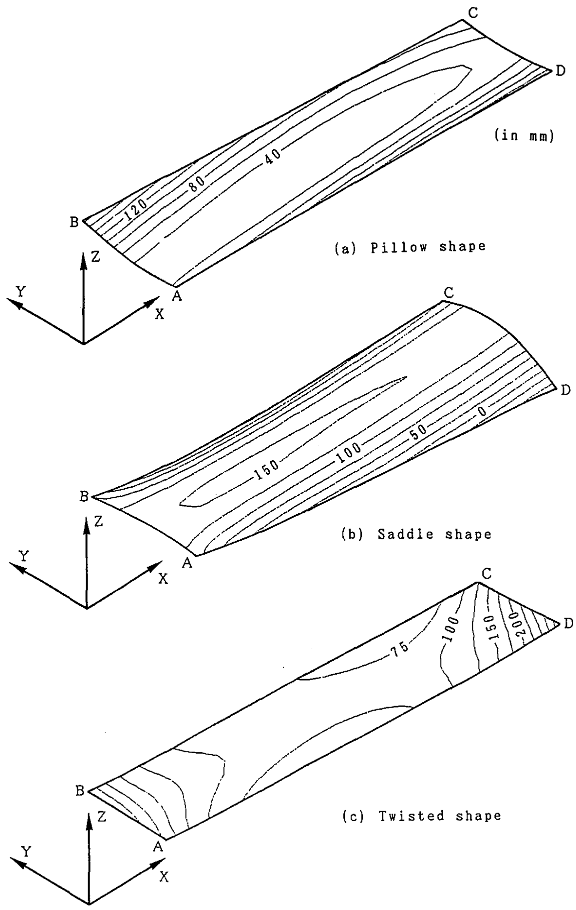


Fig. 14 Deformation of plates with bending inherent strain.

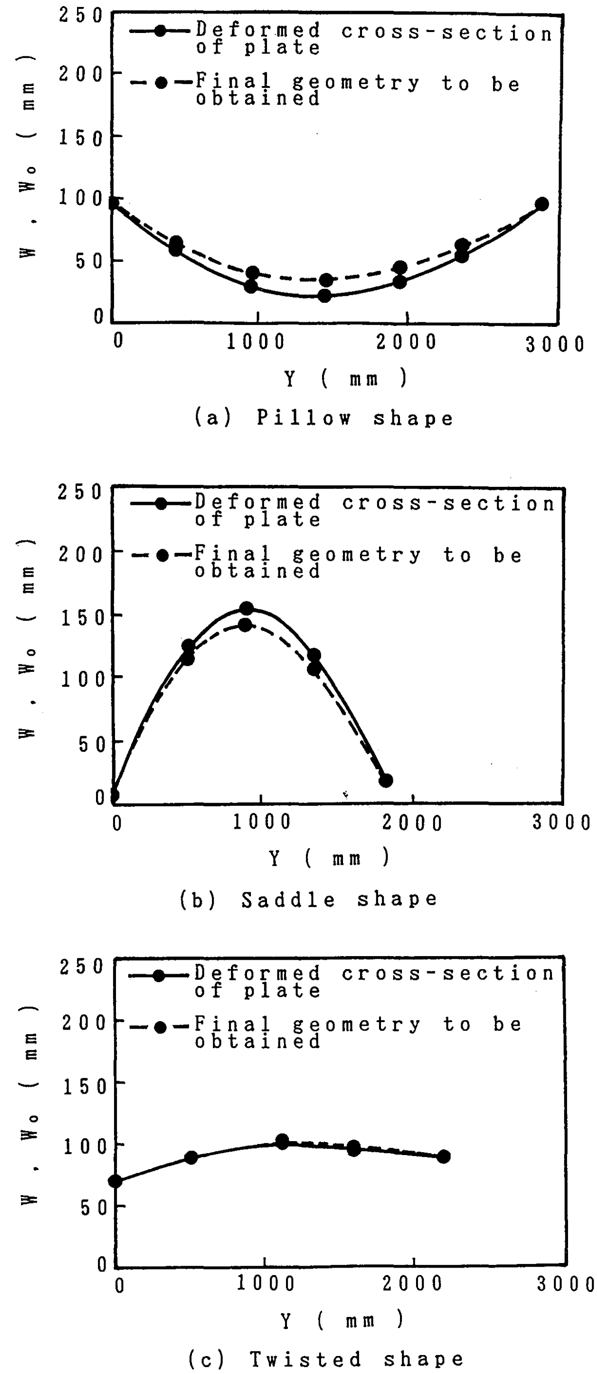


Fig. 15 Cross-sectional shape of plate with bending inherent strain.

when the bending inherent strain is given to the plate is shown in **Fig. 16** for the pillow shape. Mises equivalent stresses are shown in the figure. The miximum magnitude of inplane and bending residual stresses, σ^{m}_{max} and σ^{b}_{max}, due to giving bending inherent strain without and with gravitational force are shown in **Table 3**. The magnitudes of these stresses are relatively small compared with the yield stress level.

4.7 Position and direction of heating lines

In order to complete the forming process for the typical models, line heating process is necessary. The position and the direction of heating lines can be predicted[6] from the distribution of inplane inherent strain shown in Fig. 13. According to these distributions, the predicted position and direction of heating lines are shown in **Figs. 17-a,b,c** for the three models. They are decided based on the compressive component of the inplane inherent strain.

In the case of pillow shape, the compressive inplane inherent strain component is concentrated along the long edges AD and BC. Thus, the heating lines are located at the long edges and perpendicular to them as shown in Fig. 17-a. As it is seen from Fig. 13-a, the magnitude of the compressive inplane inherent strain is bigger in the middle part of the edges. This implies that the intensity of heating must be relatively higher for this region as shown in Fig. 17-a. If the distribution of inherent strain is examined closely, strains with significant magnitude are observed near the edge CD and these are considered as shown in Fig. 17-a. On the contrary, inplane inherent strain with small magnitude is observed near the edge AB.

For the saddle shape, the compressive inplane strain

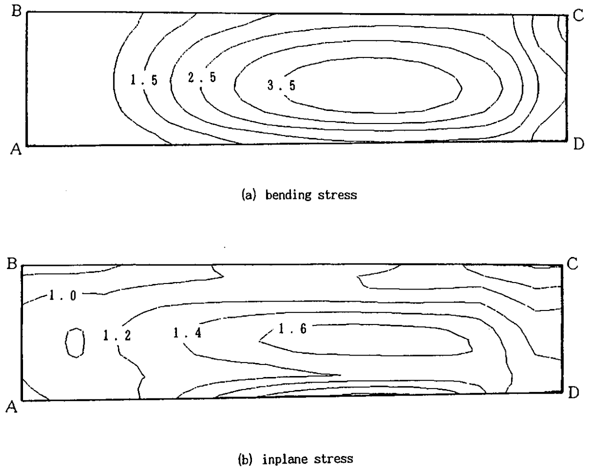


Fig. 16 Residual stress distribution in pillow shape with bending inherent strain.

Table 3 Maximum bending and inplane stresses for the three typical curved plates with bending inherent strain.

		pillow shape	saddle shape	twisted shape
stress without gravity (kgf/mm^2)	σ^b_{max}	3.04	7.95	6.54
	σ^m_{max}	2.90	7.26	4.71
stress with gravity (kgf/mm^2)	σ^b_{max}	7.84	6.40	7.14.
	σ^m_{max}	3.18	7.30	4.14

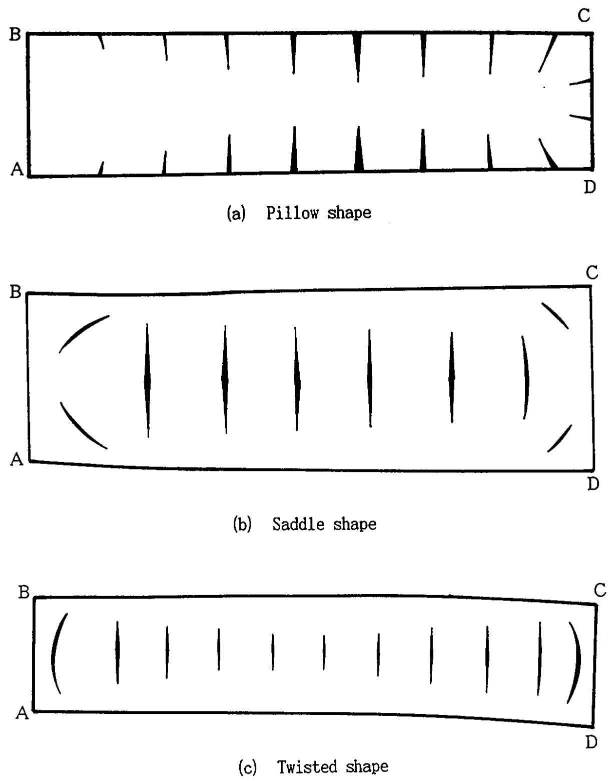


Fig. 17 Proposed position and direction of heating lines.

component is observed in the middle portion parallel to the long edges. Thus, the heating lines are perpendicular to the long edges for this portion as shown in Fig. 17-b. Pertinent to the complicated distribution of the inplane inherent strain near the edges AB and CD, the general strategy for the heating lines cannot be shown for these parts.

The same trend of the complex distribution of the inplane inherent strain exists also for the twisted shape. Two components of the inplane inherent strain are more concentrated near the edges AB and CD. While in the middle portion, the compressive inplane inherent strain nearly in one direction is observed as shown in Fig. 13-c. The correspond heating lines to this distribution is shown in Fig. 17-c.

4.8 Actual forming procedures

The actual forming procedure using rolling and line heating processes for the pillow, saddle and twisted shapes, are shown in **Figs. 18, 19** and **20**, respectively. The R. L. in the figures denotes the rolling line which is parallel to the axis of the roll machine and S. L. is the standard line for template. The solid and dotted lines denote the heating lines on the face and back sides of the plate, respectively. The open triangles shown for the pillow shape represent the heating in the triangular shape. The solid triangle denotes the wooden tempering supports and the given value represents the relative height at the corresponding point. The actual forming procedure is carried out for each model as shown in the figures with the following considerations:

pillow shape

1) The bending by roller shoud be kept less than the final curve in the transverse direction. The reason for this is that the heating of triangular shape from the concave side in the following stage causes additional bending

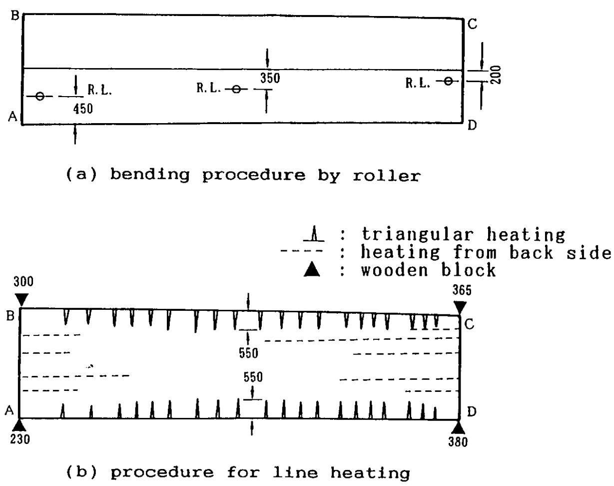


Fig. 18 Real practice for forming plate with pillow shape.

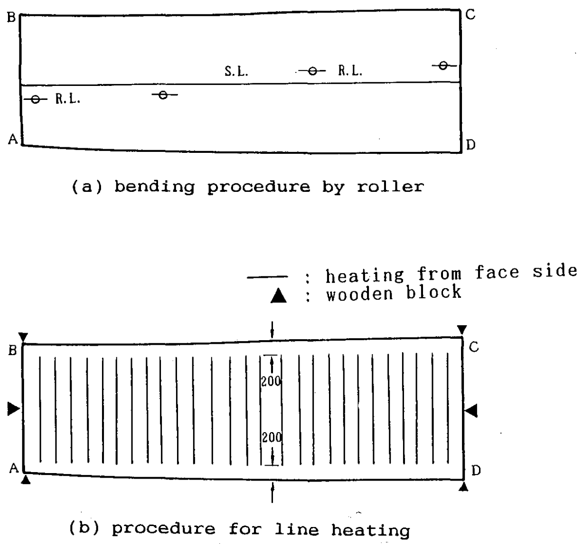


Fig. 19 Real practice for forming plate with saddle shape.

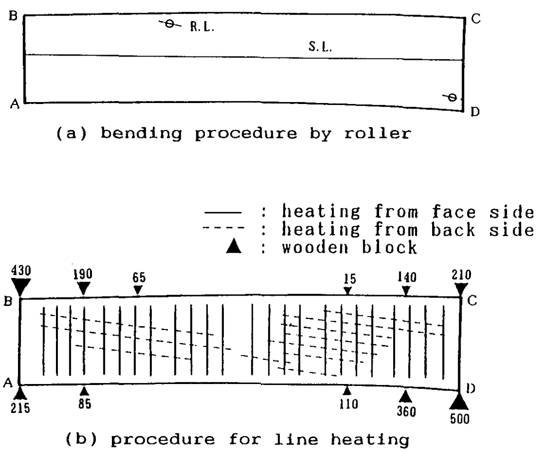


Fig. 20 Real practice for forming plate with twisted shape.

deformation of 5 mm at the point 550 mm away from the edge.

2) The intensity of triangular heating should be less near edge AB.
3) After the triangular heating, the bending deformations near the edges AB and CD exceed the desired transverse geometry by 10 mm. To remove this, the edges of the convex side is heated in the longitudinal direction.

saddle shape

1) The bending by roller should be over bend by 15~20 mm, to compensate the opening deformation caused by the following line heating process to shrink the middle part of the plate.
2) The heating line should be ended at point 200 mm away from the edge.

twisted shape

1) Bending of plate by rolling process should be over bending with tolerance of 15~20 mm because the deformation is reduced by the line heating on the convex side for contracting the middle part of the plate.
2) To correct the bending in the transverse direction which was opened by the line heating for contracting the plate, line heating in longitudinal direction is applied from the concave side.

4.9 Validity of the theoretical prediction

The forming procedures of the typical models based on the theoretical prediction as well as the practical procedures have been demonstrated in the preceding sections. The validity of the theoretical analysis can be explained as follows,

1) The general procedure predicted by the theoretical analysis is that the pillow and the saddle shapes should be formed first by mechanical process such as rolling or press, and then the line heating to produce shrinkage should be applied. In the case of twisted shape, line heating must be used to produce both bending and inplane strain. These predictions are found to agree with the real practice.
2) An excessive bending in mechanical bending process is theoretically predicted for the pillow and the saddle shapes. In the case of saddle shape, this agrees with the actual practice which recommends over bending with tolerance from 15 ~ 20 mm. However, under bending is recommended for the case of pillow shape and this disagree with the prediction. The reason for this difference may be given as follows. Although, it is assumed that the ideal inplane strain can be given in the theoretical prediction, small magnitude of bending strain may be introduced in the real line heating process. This bending strain is considered to produce additional bending deformation.
3) If the inplane shrinkage in the real practice of forming the pillow shape is actually aiming for bending, side of the plate and the direction of heating agree with the prediction.
4) The theoretical prediction and the real practice for the inplane contraction agree well each other with respect to the heating position and direction. In the case of pillow shape, the distribution of the heating intensity along the longitudinal direction also predicted correctly. However, for complex inherent strain distribution such as observed at the edge of the plate, further study is necessary to make correct decisions on the heating procedure.

5. Conclusions

This paper is devoted mainly to present a theoretical method to generate plate forming procedure using real models of curved plates in a ship structure and compare it with the real practice. The validity of the proposed method, which is given in the previous paper, to decide the position and the direction of heating lines for the real models were examined. In addition, the possibility of creating general plate forming process has been proposed and the following conclusions are obtained:

1) A method to predict the forming procedure based on the inherent strain distribution is applied to the simple twisted shape which was not exmined in the previous report. The predicted bending procedure by line heating corresponds well with the real practice.
2) An idea to design a general plate forming procedure, that combines a mechanical forming process and line heating method as well as the gravitational force, was proposed.
3) Based on the inherent strain analysis, the forming procedures of the three typical models of curved plates are examined and the theoretical prediction is found to be in good agreement with the real practice of skilled workers.

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